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Watershed Erosion and Sediment Yield Affecting Contaminant Transport

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Abstract: Relationships between sediment-associated contaminants and erosion and sedimentation processes are described, and some gaps in knowledge (with respect to erosion and sediment yield modeling) for improved understanding of contaminant transport and redistribution are identified. Watershed processes and erosion and sediment yield models are discussed. Two upland erosion models are described in detail, and criteria for application of more complex watershed models are identified and explained using example applications. New applications in modeling erosion and sediment yield are outlined, and the concept of an embedded and complex computer simulation model in an expert system is introduced.

Significant research advances have been made on environmental problems dealing with transuranics since pre-1980 work was summarized in *Transuranic Elements in the Environment* (Hanson, 1980). It appears appropriate to assess our current position with regard to an important area of this research and to present a brief overview of new techniques which may lead to significant advances in the future. The primary emphasis of this chapter is to examine erosion and sedimentation processes which have important implications in redistribution of sediment-associated contaminants (particularly the actinides) throughout the landscape.

SOIL, CONTAMINANTS, AND PHYSICAL TRANSPORT

The first chapter in Hanson (1980) is a synthesis of the research literature summarizing inventory ratios for plutonium in ecosystem compartments (Watters et al., 1980, Table 3, p. 6). The "soils compartment" is seen to be the dominant repository for plutonium. Processes which affect soil erosion and sedimentation processes also affect plutonium transport and redistribution.

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Discussions herein are limited to the hydrologic transport processes. Obviously, in some areas, wind is important in resuspension. The reader is referred to the appropriate sections in Hanson (1980) and in this publication for additional discussions of resuspension.

The section "Water Erosion" (Watters et al., 1980, pp. 26-27) discussed the limited attention physical transport processes had received in terrestrial ecosystems. Notable sources documenting these processes included Romney and Wallace (1977), Hakonson et al. (1976), Sprugel and Bartelt (1978), and Muller et al. (1978). Typically, to predict contaminant losses associated with soil erosion, the soil loss estimates were multiplied by an enrichment ratio. The eroded and transported soil particles were found to be, on the average, finer than the original soil. Moreover, the smaller particles have a larger specific surface area and, usually, a higher concentration of the sediment-associated contaminants. As a result, the eroded and transported sediments are usually enriched in fine sediments and, thus, contaminant concentration.

Unfortunately, most enrichment ratio estimates were based on measured soil and sediment data (e.g., particle-size distributions of residual and eroded sediments and their corresponding mean contaminant concentration). Little attention had been given to interpreting the measurements to determine the mechanisms controlling fine particle enrichment and, thus, determining enrichment ratios. The CREAMS model (Knisel, 1980a) and similar models were developed to account for particle-size distribution of soil and eroded, transported, and deposited sediment. The CREAMS model, for example, uses specific surface area relationships to estimate an enrichment ratio which incorporates the particle-sorting processes described earlier. Lane and Hakonson (1982) examined sediment transport rates by particle-size classes and developed an equation to predict the enrichment ratio in alluvial stream channels. Selected data on enrichment ratios relevant to plant nutrients and plutonium were summarized by Watters et al. (1983).

Problems requiring estimates of average annual erosion and contaminant yield, or statistical features of these variables, can be addressed (under specified and appropriate conditions) by models such as the USLE or CREAMS via utilization of enrichment ratios. To address more fundamental questions related to dynamic transport, deposition, and redistribution of sediment-associated contaminants, however, we must develop more fundamentally based erosion and sediment yield models.

WATERSHED EROSION AND SEDIMENT YIELD

Watershed erosion and sediment yield are the primary focus of this chapter. The terms "watershed" or "watershed processes" connote consideration of distributed systems with processes which are neither uniform in space nor constant in time. Watershed processes also suggest processes such as mass flux (water, sediment, or contaminant) relative to a specified contributing area. This contributing area is called the watershed, the drainage basin or area, or the catchment.

If one examines the landscape, and this is easier in arid and semiarid areas where geologic and geomorphic features are more readily apparent, a striking feature is that stream channels combine in complex patterns to

form the channel network and the interchannel areas. Watershed means a surface drainage area above a specified point on a stream enclosed by a topographic boundary or perimeter.

It is often convenient to visualize a watershed as consisting of the channel network and the contributing or interchannel areas. The contributing areas can be described as upland or upstream areas and adjacent or lateral areas. Sometimes, it is convenient to further characterize the watershed as consisting of the stream channel and the upland and lateral overland flow areas. The reasonableness of this characterization varies, depending upon the hydrologic systems under consideration (e.g., more accurate in agricultural and urban areas and much less so in forest environments) and upon the scale of consideration (e.g., micro vs. macro topographic features).

Background Discussion

The emphasis of our discussion is on erosion and sedimentation by water. These are the processes by which soil particles are detached, transported, and deposited by raindrop impacts, by runoff on the soil surface, and by runoff in rills, concentrated flow areas, and stream channels (see Foster, 1982, for additional discussions).

Erosion on farm fields reduces potential crop production, and sediment which leaves the field can result in subsequent sedimentation problems which, in turn, can cause off-site environmental problems (e.g., ASCE, 1975, 1982). An example is the redistribution of fallout plutonium. Erosion on other upland areas—such as construction sites, urban areas, mine developments, or other disturbed areas—can also cause on-site and off-site problems (e.g., AGU, 1977; ASCE, 1975).

Channel erosion or deposition processes can cause further problems because the stream channels are components of the watershed system (ASCE, 1975, 1982). Because we are concerned with interactive processes linking upland areas with stream channel networks, and ultimately with large river systems, we are concerned with hydrologic and hydraulic processes because they provide the driving force for erosion, sedimentation processes, and associated contaminant transport.

Form and Structure of Erosion/Sediment Yield Models

Because there are an infinite number of objectives, uses, and applications for description, explanation, investigation, understanding, and prediction of erosion and sedimentation processes, there are infinite possibilities for models. These models can be conceptual, descriptive, and/or quantitative.

Erosion and sediment yield models can be classified with respect to a large number of characteristics. Some of the most apparent and useful classifications appear in the following discussions.

A somewhat artificial distinction can be made between component and systems models. An example might be a model of watershed systems with upland and stream channel components. One can consider index vs. quantitative models. An index model might describe erosion as "moderate," whereas a quantitative model would give it as averaging 10 $g/m^2/yr$. Another useful distinction is stochastic (random processes in time) vs. deterministic models.

A useful distinction is between event models and continuous simulation models. An event model might be a set of equations to predict upland erosion given a parameter set, initial conditions, and a particular rainstorm and runoff event. In contrast, a continuous simulation model might maintain a daily water balance throughout the year to specify soil moisture status for runoff and erosion calculations as the result of a given rainstorm. An important distinction is between lumped and distributed models. For example, a lumped model might use the areal mean rainfall as input (lumped in the sense that a single value is used to represent rainfall over the entire watershed) to compute runoff volume. In contrast, a distributed model might use a three-dimensional coordinate system to describe rainfall amount as a function of x, y, and z. Parameters or variables can also be lumped in time as well as space, or both.

These classifications are important so that a model user can form a picture of how the model is classified and how it is intended to describe processes. This information, in turn, can help the user decide if the particular model is appropriate for the intended application.

WATERSHEDS AND PROCESSES

Watershed processes will be described in terms of processes occurring on upland areas, in small stream channels, and over entire watersheds. A basic-source document for these concepts is *The Fluvial System* (Schumm, 1977). An idealized fluvial system is described as consisting of Zone 1, the drainage basin as a sediment and runoff source; Zone 2, the main river channels as a transfer component; and Zone 3, the alluvial fans, deltas, etc., as zones of deposition. Further elaboration on these concepts is given by Schumm (1977) and in an American Society of Civil Engineers Task Committee Report (ASCE, 1982). The emphasis here is on Schumm's Zone 1, as further divided into upland areas, lateral areas, and small stream channels. Considered together, these three elements form the watershed.

Upland Areas

Processes considered for upland areas include runoff, sediment detachment, transportation and deposition, and sediment yield. Hydrologic and hydraulic processes, such as rainfall amount and intensity, runoff amount and rate, and flow depth and velocity drive erosion and sedimentation processes.

Runoff

Surface runoff is the result of precipitation and is the amount of water which appears in the stream channel network during and after precipitation. Surface runoff, as direct flow of water over the soil surface and in small, definable channels, is termed overland flow. Overland flow is not necessarily sheet flow, although it may be under idealized conditions and on a sufficiently small scale. It consists of flow to, into, and within small concentrated flow channels or rills (Foster, 1971, 1982). Overland flow is thus sheet flow on the interrill areas and channel flow in the many small rills. For

surface runoff to be classified as overland flow, it must be that the mean flux per unit width of the flow area cross-section is proportional to the storage in an incremental area (e.g., see Lane, Woolhiser, and Yevjevich, 1975, pp. 1-2, for a more detailed description). When surface flow cannot be hydrologically or hydraulically treated as overland flow, it is channel flow. Again, these distinctions are somewhat arbitrary and difficult to describe quantitatively, but they are useful, conceptually and mathematically.

Two general methods are available to compute runoff on small upland areas. The first method is based on models such as Richards' equation (Richards, 1931) or various approximations to it called infiltration equations. This method uses precipitation data as a function of time, together with an infiltration equation to separate rainfall rate data (intensity) into the amount entering the soil (infiltration) and the amount which moves over the soil surface (runoff as overland flow). Basic source documents dealing with infiltration include Philip (1969), Morel-Seytoux (1973), and Skaggs and Khaleel (1982).

The second method used to compute runoff on small upland areas is based on rainfall depth alone or on rainfall depth and statistics representing rainfall intensity to compute runoff volume. Given runoff volume, other procedures are used to estimate peak rate of runoff or the runoff hydrograph. The USDA Soil Conservation Service runoff curve number procedure is the best known and widely used model of this type (SCS, 1972).

Detachment, Transportation, and Deposition

A description of the detachment, transportation, and deposition processes is given by Foster (1982), and the following brief description follows that outline. Additional detail is given by Wischmeier and Smith (1978), Hjelmfelt et al. (1975), and Simons et al. (1975).

Soil particles are detached when the impact of raindrops or the erosive force of flowing water is in excess of the ability of the soil to resist erosion. Sediment particles are transported by raindrop splash and by overland flow. Deposition of soil particles occurs when the weight of the particle exceeds the forces tending to move it. This condition is often expressed as sediment load exceeding sediment transport capacity.

Particles detached in the interrill areas move to the rills by splash mechanisms and as a result of suspension and saltation in overland flow. Thus, their detachment and movement is independent (except for morphological features of rill and channel systems controlling length and slope of interrill areas) of processes in rill and stream channels. The converse, however, is definitely not true; the amount and rate of water and sediment delivered to the rills determine rill erosion rates, sediment transport capacity in rills, and rate of sediment deposition.

The basic relationship between sediment load (QS), transport capacity (TC), erosion rate (E), and deposition rate (D) is:

$$\text{Rate (E or D)} = \alpha(\text{TC} - \text{QS}) \tag{1}$$

where α is a coefficient. The coefficient for erosion is:

$$\alpha = \text{EM/TC} \tag{2}$$

where EM is the rill erosion detachment capacity rate, or the maximum erosion rate when sediment load is zero. Following Foster and Meyer (1972), the rill erosion rate equation can be rewritten as:

$$E/EM + QS/TC = 1 \tag{3}$$

where E is the erosion rate. Rewriting this equation in terms of erosion rate means:

$$E = EM(1 - QS/TC) \tag{4}$$

with the maximum erosion rate given by rearranging Eq. 2

$$EM = \alpha TC \tag{5}$$

In a similar manner, the equation for rill deposition rate (D) can be written as:

$$D/DM + TC/QS = 1 \tag{6}$$

with DM as the maximum deposition rate when transport capacity is zero. This equation can be rewritten as:

$$D = DM(1 - TC/QS) \tag{7}$$

with the maximum deposition rate given as:

$$DM = -\alpha QS \tag{8}$$

The coefficient α is given (Einstein, 1968) by the ratio of the particle fall velocity, VS, to the water discharge per unit width, q, as follows:

$$\alpha - eVS/q \tag{9}$$

where e = 0.5 for overland flow, and e = 1.0 for open channel flow.

To summarize the previous nine equations and show how sediment load may be different from transport capacity, Eqs. 3 and 7 can be rewritten as:

$$E/EM = 1 - QS/TC \tag{10}$$

for erosion, and

$$D/DM = 1 - TC/QS \tag{11}$$

which, in terms of relative sediment load (QS/TC), can be written as:

$$D/DM = 1 - 1/(QS/TC) \tag{12}$$

Note that Eq. 10 shows the potential relative erosion rate, E/EM is a linear function of relative sediment load. Equation 12 shows relative deposition rate is proportional to the reciprocal of relative sediment load. These relationships are shown in Fig. 1.

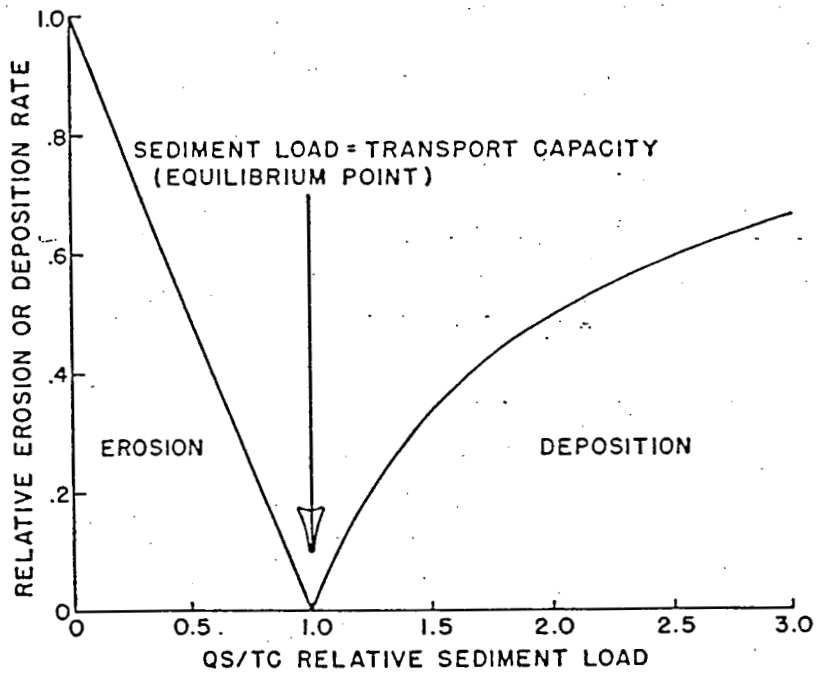

Fig. 1. Schematic illustration of relationships between potential erosion rate, transport capacity, and deposition rate.

The curves shown in Fig. 1 suggest the following:

1. Potential erosion rate is at its maximum when sediment load is zero, such as when clear water is directly introduced into the upstream end of a rill or channel.
2. Relative erosion rate decreases linearly with increasing sediment load until net erosion ceases when sediment load exactly equals sediment transport capacity.
3. Deposition rate is at its maximum when transport capacity is zero, such as when flow velocity is zero in still water.
4. Relative deposition rate decreases nonlinearly from its maximum with decreasing sediment load until net deposition ceases when sediment load exactly equals sediment transport capacity.

Transport capacity tends to increase with increasing flow and flow velocity. For the same flow conditions, transport capacity—for smaller or lighter particles—is greater than it is for larger or heavier particles. There-

fore, many factors influence transport capacity and, thus, sediment yield. For example, the flow transport capacity in a rill or channel may exceed available sediment load. If the detachment capacity (ability to dislodge soil particles) is less than the resistance of the soil to detachment by flow, then rill or channel erosion will not occur, and transport capacity will remain in excess of sediment load in the channel. On the other hand, if the transport capacity of a channel is less than available sediment supply from interrill erosion, then deposition will occur. Consider a short rill near the top of a hillslope. Flow rate increases nearly linearly with distance from the top of the slope (at least at steady state) so that transport capacity increases with increasing slope length x. For a fixed x, increasing interrill detachment rate can result in direct increases in sediment yield if sufficient transport capacity in the rill exists. If transport capacity in the rill is much less than the sediment supply from interrill erosion, then increasing the interrill detachment rate may not result in corresponding increases in sediment yield. The increased sediment supplied from interrill areas may be deposited in the rills, as shown in Fig. 1 and by Eq. 12.

Foster (1982, p. 301) summarizes this latter point by saying, "Most downslope movement of upland sediment is by flow in the rills. Even though excess transport capacity may exist on the interrill areas, this transport capacity does not add to the transport capacity of flow in the rills. This is subtle but a key point in using data from small experimental areas (e.g., 1 m by 1 m) to estimate parameter values for erosion models. Conversely, excess transport capacity in the rills is not available to transport sediment detached by raindrop impact on interrill areas." This is a key point for practical application of erosion equations and, thus, merits further elaboration.

Small rainfall simulators (on the order of 1 m × 1 m plots) are often used to estimate parameters in erosion models and to estimate the erosional impacts of various land use and treatments. These simulators, on very small plots, can distinguish between various treatments as they affect interrill detachment rates and can be very efficient in estimation of interrill erosion parameters in erosion/sediment yield models. They cannot be used to investigate rill and channel processes, nor can they be used to estimate rill and channel erosion, transportation, or deposition parameters.

Erosion data and parameter estimates, obtained using these 1 m × 1 m plots, are often found to be in disagreement with data and parameter estimates from larger plots or watersheds. These results are sometimes incorrectly used to question data and models derived from larger plots and small watersheds. Although these large plot- and watershed-derived data and models will, and should, be subject to critical analyses, their applicability and worth should not be judged exclusively in relation to how well they agree with small plot results.

Sediment Yield

Sediment yield from upland areas is simply the final and net result of detachment, transport, and deposition processes occurring from the watershed divide down to the point of interest where sediment yield information is needed. Depending upon the scale of investigation and definition of

the problem, this point of interest can be a position on a hillslope, a property boundary at a construction site, the edge of a farm field, delivery point to a stream channel, or some other location dependent upon topography. In any event, sediment yield at the point of interest is determined by the occurrence of physical processes of sediment detachment, transport, and deposition at all positions in the contributing watershed area above the point of interest.

Sediment yield is often discussed (and computed) based on the use of a delivery ratio defined as the change per unit area from the source to the point of interest. The delivery ratio (D in percent) is often expressed as:

$$D = 100\,Y/T \tag{13}$$

where Y is the total sediment yield at the downstream point of interest, and T is the total material eroded (gross erosion) on the watershed area above the point of interest. Values of Y and T are given in units of mass per unit area per unit time (e.g., T/A/yr). Descriptions of sediment yield from upland areas are given in Foster (1982, pp. 362-369) and from larger watersheds in *Sedimentation Engineering* (ASCE, 1975, pp. 437-494) and Williams et al. (1985). The emphasis in this section is on upland areas and the delivery of water and sediment to the stream channel system and, ultimately, the watershed outlet.

Stream Channels

As interest in erosion and sediment yield extend to progressively larger land areas, the relative importance of stream channels increases. There are no rigorous and clear-cut criteria, however, used to set definitive limits to distinguish between rills and small streams or channels. If normal tillage can obliterate the concentrated flow areas, they are termed rills. If not, they are termed gullies or channels (Hutchinson et al., 1976; Foster, 1982). In a more recent Task Committee Report (ASCE, 1982, p. 1330), a small channel was defined as follows:

> Therefore, for this report, we adopt an operational definition of a small stream or channel as a permanent feature of the landscape that conveys water and sediment from the upland areas to the major channels and acts as a sediment source or sink, depending upon the dynamic characteristics of the water-sediment flow system. Central to this definition is the sensitivity of the small channel to upland runoff and erosion processes and to hydraulic and sediment transport processes in the larger downstream channels.

Notice this latter definition shares the concept of permanent feature of the landscape with the agricultural definition. As unsatisfactory as these definitions may be, they do reflect the state of the art in hydrology, erosion and sedimentation, and geomorphology.

Individual Channel Segments

Discharge along a single channel segment during a runoff event, and in the absence of significant infiltration losses to the channel bed and banks, can be assumed to vary directly with upstream contributing areas. If an initial discharge is allowed at the upper end of a segment to approximate flow

from headwater contributing areas, then the channel segment has an upstream inflow and increasing discharge in the downstream direction due to lateral inflow.

Foster et al. (1981, p. 1256) described this flow situation in farm fields and its representation in the CREAMS model as follows:

> Flow in most channels in fields is spatially varied, with discharge increasing along the channel. The model approximates the energy gradeline along the channel assuming a triangular channel section and steady flow at the characteristic peak discharge from a set of polynomial curves fitted to solutions of the normalized spatially varied flow equation (Chow, 1959). This feature approximates either drawdown or backwater at a channel outlet like the edge of a field where vegetation may hinder runoff. As an alternative in the model, the slope of the energy gradeline can be assumed equal to the channel slope. After the slope of the energy gradeline is estimated, a triangular, rectangular, or naturally-eroded section is selected at the user's option to compute flow hydraulics and channel erosion and sediment transport.

This description of channel segment representation in the CREAMS model (Knisel, 1980a) points out several important features of runoff and flow hydraulics in small channels. Of course, flow in these channels is spatially varied, and various options are available in approximating channel flow. Foster et al. (1981) selected a characteristic discharge (the peak discharge) and then assumed spatially varied, but steady, flow. Others have assumed uniform, but unsteady, flow. Still others have assumed bed slope equal to friction slope and have thus applied the kinematic wave equations. Even application of the dynamic equations requires several simplifying assumptions (e.g., Chow, 1959) and results in approximate flow calculation. Moreover, the flow perimeter (channel bed and banks) is itself variable and dependent upon flow conditions and is often termed self-formed (ASCE, 1982). Processes of alluvial bed forms, and their interaction with flow hydraulics and sediment transport, are important (Simons and Richardson, 1971).

Relationships between erosion, sediment load, and deposition—discussed in the section on rill erosion—also apply; therefore, upland processes affecting water and sediment supply to the stream channels also affect processes in the channels. Localized changes in hydraulic conditions affect erosion, transport, and deposition of sediment in rills and have similar effects if they occur in channels.

Small Watersheds

Upland processes and processes in individual channel segments are combined through the channel network and interchannel areas to influence runoff and sediment yield from watersheds. In addition to the complex relationships on upland areas in stream channels, processes affecting watershed runoff and sediment yield include interactions (e.g., channel junctions and backwater) as well as land use, soil and cover characteristics, and other factors varying over the drainage area. The state-of-the-art in hydrology and erosion/sedimentation is such that runoff and sediment yield from a watershed cannot be described adequately or predicted without resorting to use of indices, fitted parameters, and the application of judgment and experience.

This does not mean that significant progress has not been made or will not be made in the future. For example, the recent publication of the American Society of Agricultural Engineers monograph, *Hydrologic Modeling of Small Watersheds* (ASAE, 1982a), represents a compilation of nearly two decades of significant advances over similar material included in the *Handbook of Applied Hydrology* (Chow, 1964).

Two important factors may assist in development of improved hydrologic and sediment yield models. First is the growth and increasing availability of personal computers and telecommunications links to major computer centers and data repositories. Second is the development of artificial intelligence, especially expert systems. These systems will allow compilation and ready access to the expert judgment and experience factors necessary to predict runoff and sediment yield from watersheds. Development of expert systems will be discussed in a later section of this chapter.

DEVELOPMENT OF MODELS

The first models examined will deal with soil loss on upland areas. Next, the emphasis will be on simple watersheds. Finally, we will return to a brief discussion of models for runoff and sediment yield from larger and more complex watersheds.

The Universal Soil Loss Equation (USLE)

The most widely used and successful model to predict soil loss from upland areas is the USLE described by Wischmeier and Smith (1978). Their publication, *Predicting Rainfall Erosion Losses, A Guide to Conservation Planning*, states on page 1:

> The procedure is founded on an empirical soil loss equation that is believed to be applicable wherever numerical values of its factors are available. Research has supplied information from which at least approximate values of the equation's factors can be obtained for specific farm fields or other small land areas throughout most of the United States. Table and charts presented in this handbook make this information readily available for field use.

Several important points are made in these introductory comments. The phrase "an empirical soil loss equation" suggests the origin and basis of the equation. The equation and its factors are based on observations of erosion and erosion processes rather than theoretically derived relationships. The phrase "research has supplied information" makes reference to a data base, consisting of over 10,000 plot-years of data from 37 locations in 21 states, used to develop the USLE. Since its development, additional plot data have been collected in many other states and countries to evaluate USLE factors under a variety of conditions. These efforts will, no doubt, continue for the foreseeable future. The phrase "for specific farm fields or other small land areas" limits the intended application to upland areas, described earlier, and emphasizes agricultural systems, especially farm fields. The phrase "Table and charts presented . . ." illustrates the methodology used to prepare the handbook and its intended level of use as a tabular and graphical handbook. Finally, the handbook is intended to help in choosing guidelines for selection of erosion control practices on farms and other erosion-prone areas.

Wischmeier and Smith (1978, p. 3) also state: "The USLE is an erosion model designed to predict the long-time average soil losses in runoff from specific field areas in specified cropping and management systems." This comment can be interpreted to mean that the USLE is intended to compute average annual soil loss, and the result should be seen as a long-term average annual value.

The USLE was originally derived and presented in English units. Conversion to SI units was accomplished after the fact. Therefore, for readers' convenience, the presentation herein provides both English and SI units. The USLE is:

$$A = RKLSCP \tag{14}$$

where the terms are described as follows:

The variable A is the computed soil loss per unit area and is most often expressed as an average value in English units as ton/acre/yr and in SI units as t/ha/y.

Rainfall and Runoff Factor

The R factor is described as a rainfall and runoff factor and is computed as the product of rainfall storm energy (E) and the maximum 30-min rainfall intensity (I30). The product term (EI) is described by Wischmeier and Smith (1978, p. 5) as "a statistical interaction term that reflects how total energy and peak intensity are combined in each particular storm. Technically, it indicates how particle detachment is combined with transport capacity." Total energy refers to raindrop detachment, and peak intensity refers to the peak rate of runoff. The R factor is often misinterpreted as a rainfall factor only. If one conducts regression analyses with data from small upland areas, however, I30 is often most strongly correlated with runoff volume or peak rate of runoff. To the extent that regression equations summarize a data set and result in prediction ability, I30 is a runoff predictor in the R factor.

The energy parameter can be computed from rainfall intensity data using:

$$E = 916 + 331 \operatorname{Log}_{10} I \qquad I \leqslant 3 \text{ in./hr} \tag{15}$$

$$E = 1074 \qquad I > 3 \text{ in./hr} \tag{16}$$

where E is kinetic energy in hundreds of foot-tons per acre-inch, and I is intensity in inches per hour for a given period of constant rainfall intensity. Values of E for I greater than 3 in./hr are assumed to be given as E = 1074 as an upper limit. Equation 15 is applied over each interval in a storm, and the sum is rainfall energy. Tabular data for rainfall energy computation are

also given in Table 19 on p. 56 of Wischmeier and Smith (1978). In SI units, the corresponding equations are:

$$E = 0.119 + 0.0873 \, \mathrm{Log}_{10} I \quad I \leq 76 \, \mathrm{mm/h} \tag{17}$$

$$E = 0.283 \quad I > 76 \, \mathrm{mm/h} \tag{18}$$

where E now has units of megajoule per hectare per millimeter of rainfall (MJ/ha·mm), and I is rainfall intensity in mm/h. Following the notation of Foster et al. (1981), hour and year, in English units, are written hr and yr, while hour and year, in SI units, are written as h and y.

Figures 1 and 2, in Wischmeier and Smith (1978), show average annual values of rainfall erosion index for the United States. These maps can be used to estimate R for use in the USLE. An approximate equation to estimate R is:

$$R = 27.38 \, P^{2.17} \tag{19}$$

where R is an estimate of the average annual rainfall erosion index in (foot-tons per acre) (in. per hr), and P is the 2-yr, 6-hr rainfall amount in inches.

The corresponding equation, in SI units, is:

$$R = 0.417 \, P^{2.17} \tag{20}$$

where R is in MJ·mm/ha·h·y, and P is the 2-y, 6-h rainfall amount in millimeters.

Therefore, if storm rainfall intensity data are available, then a value of E can be computed for each storm by summing over uniform intensity periods within each storm. These summed individual storm values are multiplied by the corresponding I30 values for each storm and are summed over the entire year. This annual value of EI is divided by 100 as a value of R for that year. If this procedure is repeated over several years, an average annual value of R can be estimated. If rainfall intensity data are not available or are unsuitable because of short records, etc., then Figs. 1 and 2 in the USLE Handbook can be used to estimate R. Finally, a rough approximation is given by Eq. 19 or 20.

Within the continental United States, annual values of R range from <20 to >550 hundreds of ft-tons·in./acre·hr·yr, or from <340.4 to >9361 MJ·mm/ha·h·y.

Soil Erodibility Factor

The soil erodibility factor, K, in units of (tons/acre) (acre/ft-tons) (hr/in.) or t·ha·h/ha·MJ·mm, is the soil loss rate per erosion index unit for a specified soil as measured on a unit plot. A unit plot is defined as a 72.6 ft, or 22.1 m, length of uniform 9% slope continuously in clean-tilled fallow condi-

tion. Note that under these unit plot conditions, LS = 1, C = 1, and P = 1 so that LSCP = 1. With these values, it must be that A = RK, so that if R is plotted on the horizontal axis and A is plotted on the vertical axis, then K is the slope of the line through the origin expressing A as a function of R.

Figure 3, on p. 11 of the USLE Handbook (Wischmeier and Smith, 1978), is a nomograph for K as a function of percent sand, silt, clay, and organic matter, as well as soil structure code and soil permeability class. Computed values of K range from about 0.02 to 0.70 ton·acre·hr/hundreds of acre·ft tons·in., or from 0.0026 to 0.092 t·ha·h/ha·MJ·mm, with most agricultural soils having values in the range of 0.10 to 0.40, or 0.013 to 0.053 in SI units (e.g., Table 1, p. 9 of the USLE Handbook).

Slope Length and Steepness Factor

The factor LS is dimensionless and is the expected ratio of soil loss per unit area of a field slope to that from a unit plot. A 72.6 ft (22.1 m) uniform slope at 9% would have an LS value of 1.0. Table 3 on p. 12 and Fig. 4 on p. 13 of the USLE Handbook give LS values for various combinations of slope length and steepness. For example, a uniform slope length of 25 ft (7.6 m) would have an LS value of 0.06 for 0.2% slope and a value of 2.04 for 20% slope steepness. These estimates are based on data from plots with slopes ranging from 3 to 18% steepness and 30 to 300 ft (10 to 100 m) in length. Within these limits, LS values range from a low of about 0.2 to a high of about 6.

Cover and Management Factor

The cover and management factor, C, is dimensionless and is the ratio of soil loss from an area with specified cover and management to that from an identical area in tilled and continuous fallow. The C factor is a measure of the combined effects of all cover and management variables affecting soil loss and is the most difficult factor to estimate (under most conditions except the unit plot) in the USLE. At a particular site, once K, LS, and P have been measured or specified, then R can be measured or calculated. The C factor is then determined over time (cover and management practices take time to implement, and their combined and interactive influences may take months or years to stabilize) and on a mostly empirical basis. Moreover, because vegetative cover develops over time and with the seasons, as controlled by plant physiology, climate and weather, management, soil characteristics, etc., it is highly dynamic and highly variable. Therefore, the C factor lumps an enormous amount of information on biological, chemical, physical, and land use or management-induced variability into a single coefficient. Under these conditions, its specification involves a great deal of judgment and subjectivity based upon empirical data and experience. Moreover, the reliability of C factor estimates is a function of all these interactive and ill-defined relationships, so that true measures of its variability are impossible in the objective sense and are data- and judgment-based in a heuristic sense.

Within each climatic zone, there are periods during the year when highly erosive rainfall episodes are expected (subject to localized and short-term weather patterns), as are periods of poor to good plant cover. Therefore, for

the same soil, topography, rainfall energy, etc., if the degree of correspondence between rainfall periods and plant growth stages varies between regions, then the values of C, for the same cropping system, will vary between the regions. Under these conditions, it is necessary to derive C factors for the localized climatic and plant growth relationships.

The USLE Handbook describes various items affecting estimated C factors as follows:

1. Cropstage periods to represent the seasonal changes in effectiveness of plant cover.
2. Crop canopy as a measure of the degree of protection provided by the canopy.
3. Residue mulch as a measure of "on-ground" protection from raindrop impact.
4. Incorporated residues affecting the top few inches of soil.
5. Tillage as it affects the soil, residues, etc.
6. Land use residuals such as the influence of plant roots, organic matter, and other factors of interseasonal importance.

Table 5, pp. 22 through 24 of the USLE Handbook, lists several hundred soil loss ratios for croplands. Values in Table 5 range from .01 to 1.40, representing soil loss ratios of from 1 to 140% of the soil loss from a continuous fallow plot. Entries in Table 5 include cover, crop sequence, and management, as well as spring residue and percent cover after planting, cropstage from fallow to seedbed preparation, and crop cover from seedbed to complete canopy cover. Tables 6 through 12 and Figs. 5 through 9, in the USLE Handbook, present additional information on estimating C factors for other cropping practices for pasture and rangeland sites and for climatic adjustments for seasonal variations in EI.

Research efforts are under way throughout the United States, and in several other countries, to determine C factors under a variety of conditions. Two general approaches are used separately and in combination. First is the subfactor approach, in which C for a particular situation is estimated based on the known influence of component processes via a subfactor approach. The second method is to transport portable rainfall simulators to various locations to derive on-site estimates of C factors using simulated rainfall. These efforts are producing additional estimates of C factors beyond those summarized in the USLE Handbook.

Support Practice Factor

The support factor P is dimensionless and is a factor used to represent the ratio of soil loss with a specific support practice to the soil loss on a unit plot. The most important support practices for cropland are contour tillage, strip-cropping on the contour, and terrace systems. The P factor is described (for croplands) on pp. 34 through 39 of the USLE Handbook. Values of P for contouring range from about 0.6 to 0.9, for strip-cropping about 0.3 to 0.9, and for contour-farmed and terraced fields, from about 0.05 to 0.9. Therefore, a reasonable range for P is from 0.05 to 1.0, depending upon the site-specific conditions described in the USLE Handbook.

General Comments

The USLE, as an empirically derived and data based model, shares the strengths and weaknesses of such procedures. In terms of its main factors (RKLSCP), it is a linear equation, but in terms of how physical features and management practices affect the factors, it is nonlinear. For example, LS is a nonlinear function of slope length and steepness, and C is a nonlinear function of the percent mulch cover.

The USLE is intended to estimate long-term average annual soil loss from upland areas. The emphasis in development of the equation was on agricultural areas of the humid United States. Users and potential users should keep these two facts in mind in application of the USLE.

The USLE has provided a focus and a methodology of conducting erosion and soil conservation research for decades. As a method for focusing research and as a method for summarizing research data representing complex processes and interactions, the USLE has served a useful purpose. The USLE is the most widely known and accepted method of predicting erosion and of evaluating the influence of erosion control methods. The equation, and its associated methodology, will probably be used in these ways for the foreseeable future. Research scientists and users, however, should not see the USLE as a true and final representation of erosion, erosion prediction, and erosion research. The USLE is a step in our continuing efforts to develop understanding and improve models to estimate erosion and sediment yield.

Models for Erosion Dynamics on Upland Areas

A large number of erosion-sediment yield models have been developed. Some of these models use the USLE as a starting point and improve or elaborate upon particular components or processes. Others begin formulating erosion/sediment yield processes independently of the USLE structure, and solve the resulting equations. Foster (1982) summarizes several of these models in tabular format, and Knisel (1980b) discusses several models. Although all of these models are in some way related to the USLE, a useful classification is whether or not the model is directly related to the USLE.

USLE Modifications

Onstad and Foster (1975) modified the R factor in the USLE to explicitly account for rainfall and runoff separately. This modification was intended to allow individual storm (rather than long-term average) estimation of upland soil loss. All other factors in the USLE retained their original interpretation and meaning.

Williams (1975) modified the USLE (called MUSLE for "Modified USLE") to replace the R factor by a runoff factor and to interpret the other USLE factors on a watershed-wide basis. Thus, MUSLE is really a watershed, rather than an upland, sediment yield model and will be discussed in greater detail later.

The ANSWERS model (Beasley, 1977) is a complex and distributed model to estimate erosion and sediment yield in time steps during a storm and over a watershed for individual runoff events. This is a watershed, rather than an upland model, but is based, in part, on USLE parameters and factors. The

CREAMS model (Knisel, 1980a) estimates erosion and sediment yield on an individual storm basis (not dynamics during or within the storm, as in ANSWERS) and incorporates some USLE parameters and factors. The CREAMS model will be discussed in greater detail later.

Other Upland Models

Of all the alternative formulations of erosion dynamics on upland areas, the most useful for the present discussions are those directly coupled with the kinematic wave equations for runoff on a plane. Other formulations or models, consisting of a cascade of planes and channels to represent an entire watershed, could be considered. For the present discussions, however, emphasis will be on a single plane used to represent upland or lateral overland flow areas.

Kinematic wave equations for overland flow on a plane have been shown to apply (with consequent parameter distortions dependent upon the degree of surface irregularity) to many irregular surfaces (e.g., Woolhiser, Hanson, and Kuhlman, 1970). Such surfaces can include topographically simple upland areas on natural watersheds. For these conditions, the one-dimensional kinematic wave equations for a plane are:

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = p(t) - f(t) \tag{21}$$

and

$$q = Kh^m \tag{22}$$

where h = local depth of flow per unit width
q = runoff rate per unit width
p(t) = rainfall rate
f(t) = infiltration rate
K and m = parameters
t = time
x = distance down the plane

Equation 21 is the continuity equation, and Eq. 22 is the simplified momentum equation, in which the friction slope is assumed equal to the slope of the plane (see Huggins and Burney, 1982, as a recent reference describing these equations). In general, p(t) and f(t) are given by complex and numerical, rather than analytical, functions, so that Eqs. 21 and 22 are solved numerically.

The continuity equation for sediment particles traveling with the mean water velocity is given by:

$$\frac{\partial ch}{\partial t} + \frac{\partial q_s}{\partial x} = EI + ER \tag{23}$$

where c = sediment concentration
q_s = sediment discharge rate per unit width
EI = interrill erosion rate
ER = rill erosion rate

Notice that EI and ER are complex functions of many factors, as described earlier.

Based upon previous work (Foster, Meyer, and Onstad, 1977; Hjelmfelt, Piest, and Saxton, 1975; Shirley and Lane, 1978; Lane and Shirley, 1982), several assumptions for Eqs. 21 and 22 can be made which allow derivation of analytic solutions. If the difference between rainfall and infiltration rates in Eq. 21 can be approximated as a step function [i.e., $p(t) - f(t) = r$], then analytic solutions to the runoff equations are available. If we further assume that $q_s = cq$ and define EI and ER as

$$EI = KIr \tag{24}$$

and

$$ER = KR(Bh^m - qs) \tag{25}$$

where r = rainfall excess rate
KI = an interrill coefficient
KR and B = rill coefficients

The other variables are as described above. If we further let

$$Bh^m = (B/K)q \tag{26}$$

then Eqs. 21 through 26 form a kinematic wave model for runoff and erosion on a plane.

Foster, Meyer, and Onstad (1977) specified the approximate forms of the erosion equations (Eqs. 23 through 25). Hjelmfelt, Piest, and Saxton (1975) derived an analytic solution to the model (Eqs. 21 through 26) for the rising portion of the hydrograph but not for the entire hydrograph. Shirley and Lane (1978) solved the equations for the entire hydrograph and derived a sediment yield equation by integrating the solution to the model. Lane and Shirley (1982) applied the model to runoff and sediment data from erosion plots and a small watershed to derive parameter values.

The solution to the model (Eqs. 21 through 26) is runoff rate $q(x,t)$, sediment concentration $c(x,t)$, and thus, sediment discharge rate $q_s(x,t) = c(x,t)\,q(x,t)$ as functions of distance (x) and time (t). These solutions are integrated with respect to time to produce a sediment yield equation QS(x) as

$$QS(x) = Q(x)\,[B/K + (KI - B/K)\,F(x)] \tag{27}$$

where QS(x) = sediment yield as a function of distance down the plane
Q(x) = runoff volume at x
F(x) = a function of (x)

The other variables are described above. The function F is given as

$$F(x) = [1-\exp(-KRx)]/(KRx) \tag{28}$$

Now, if both sides of Eq. 27 are divided by the total runoff volume, Q(x), then Eq. 29 becomes an equation for the time-average sediment concentration as a function of distance. That is,

$$\overline{C}(x) = B/K + (KI - B/K)\,F(x) \tag{29}$$

is an equation for the time average sediment concentration during a runoff event and at a particular x.

The limit of F(x), as x approaches zero, is 1.0, so that in the limit

$$\overline{C}(0) = CO = KI \tag{30}$$

is an expression for the initial concentration as runoff begins. Notice that CO = KI is a statement that the initial concentration (at x = 0 and t = 0 and, in fact, at t = 0 for all x) is equal to the interrill detachment rate.

The limit of F(x), as x approaches infinity, is zero, so that in the limit,

$$\overline{C}(\infty) = B/K \tag{31}$$

is an expression for the time average sediment concentration for infinite distances down the plane. Notice that Eq. 31 can be interpreted as a limiting case where sediment concentration approaches the sediment concentration corresponding to transport capacity in the rills.

Therefore, the quantity (KI − B/K) can be used as a measure of how this upland model deals with detachment capacity, transport capacity, and sediment load. If B/K is less than KI, then interrill detachment rate is always in excess of rill transport capacity. Under these conditions (1) at any particular time, sediment concentration will decrease with distance down the plane, and (2) at any particular distance, sediment concentration will decrease with time during the period of runoff. If B/K is exactly equal to KI, then sediment concentration is constant with time and uniform with space during runoff because interrill detachment rate is exactly equal to rill transport capacity. If B/K is greater than KI, then rill transport capacity is always in excess of interrill detachment rate. Under these conditions (1) at any particular time, sediment concentration will increase with distance down the plane, and (2) at any particular distance, sediment concentration will increase with time during runoff.

In the first case (B/K < KI), sediment yield will be limited by transport capacity in the rills. The second case (B/K = KI) is a steady-state and uniform case and is highly unlikely. In the third case (B/K > KI), sediment yield will be limited by interrill detachment if net rill erosion is limited, or by the rill erosion rate if significant rill erosion occurs.

In terms of the USLE parameters, case 1 (B/K < KI) is likely to occur on shallow slopes with erodible soils and little cover protection (low LS, high K, and high C factors). Case 3 is likely to occur on steep slopes and some cover protection (high LS, moderate to low K, and low to moderate C factors).

An approximate, but useful, rule-of-thumb for field observations is as follows:

1. Case 1 (B/K < KI, transport capacity limited): look for rills, if apparent, with rectangular or trapezoidal cross-sections and flat, sandy bottoms; and small stone or other mulch elements suspended on columns suggesting they provided protection from raindrop impact.
2. Case 3 (B/K > KI, detachment limited) look for rills with incised bottoms in a V-shape, and stair-stepped longitudinal slope in the rills characterized by small headcuts or nick points.

Of course, the observer should expect to see all of these conditions during field inspections, so interpretation will be a matter of sampling method, sampling frequency, extent, and judgment.

The results summarized above are for simplifying assumptions necessary to obtain analytical solutions to Eqs. 21 through 23. More realistic assumptions on the infiltration process, or more complex geometries consisting of cascades of planes and channels, require numerical solution of the basic equations. Foster (1982, pp. 370 through 372) summarized several important contributions in this area of modeling and provides comments useful in selecting an appropriate model for a particular application.

Watershed Models

Watershed models used in computation of sediment yield from watersheds vary in complexity, depending primarily upon two considerations. The first consideration is the level of detail represented by the equations comprising the model and is a measure of the conceptual and mathematical complexity. The second consideration for a particular model is the size and complexity of the prototype watershed represented by the model. For the present discussion, models for overland flow with sheet and rill erosion are classified as upland models. If channel processes are included in the model representation, then it is termed a watershed model. Under these criteria, the USLE is an upland model, whereas the CREAMS model (although a field-scale, as opposed to basin-scale model) is a watershed model because it includes channel processes. The CREAMS model, however, can only deal directly with watersheds characterized by overland flow contributing to a channel segment. Other models, such as ANSWERS, can simulate sediment yield from watershed with complex channel networks. Foster (1982) presents a summary of many important models, and Knisel (1980b) presents an overview of erosion and sediment yield models.

Selected models which incorporate a lumped, or index, approach to estimation of sediment yield are summarized in Table 1. The MUSLE (Williams,

TABLE 1

Summary of Selected Models as Lumped, Simplified, or Index Procedures to Estimate Watershed Erosion and Sediment Yield

Model	Reference	Comments
MUSLE	Williams (1975)	Modification of USLE using runoff volume and peak rate in place of the R factor. Sediment yield equation for individual storms.
PSIAC	PSIAC (1968)	Classification method involving nine factors (high, moderate, and flow) to estimate annual sediment yield in Pacific-Southwest.
Flaxman	Flaxman (1972)	Regression equation for reservoir design in the West. Average annual sediment yield.
Delivery ratio	ASCE (1975); ARS (1975)	Basic references for delivery ratio approach in estimating sediment yield.

1975) approach uses USLE factors (averages over a watershed area), except that the R factor is replaced by a function of runoff volume and peak rate of runoff. This model is relatively easy to use and has been applied on a large number of watersheds. The PSIAC (1968) model was developed as an index, or classification, method involving factors representing geology, soils, climate, runoff, topography, ground cover, land use, upland erosion, and channel erosion/sediment transport. These factors are combined to produce a rating factor. Based upon the rating, average annual sediment yield is estimated as being in one of five intervals or ranges. Flaxman's method (Flaxman, 1972) is based upon a regression equation involving average annual precipitation and temperature, average watershed slope, and soil factors. The last entry in Table 1 does not refer to a specific model but to a technique or methodology called the delivery ratio approach. The cited references provide basic information on background and the specific form of the equations used to approximate a delivery ratio.

Selected models, which incorporate a simulation approach to estimate runoff sediment yield from watersheds, are summarized in Table 2. The Negev (1967) model is based on an early hydrologic simulation model, the Stanford Watershed model (Crawford and Lindsley, 1962). As such, it represented a method of driving erosion/sediment yield models using a hydrologic model and directly incorporated runoff rates and amounts, rather than runoff indices. A comprehensive watershed model, called the CSU model in Table 2, was developed at Colorado State University. The model includes overland and open channel flow, bedload and suspended sediment, and sediment routing by particle-size classes. Many of the parameters can be estimated from previous analyses, and the number of parameters requiring calibration will probably decrease in the future, as the model receives wide use. As for all basin scale models, the amount of parameter distortion, caused by lumping as watershed size increases, is unknown. The ANSWERS model was developed primarily for agricultural areas, and thus makes use of some USLE parameters. It is based on a grid network scheme to segment a watershed so that it shares the strengths (repeatability, compatibility with

TABLE 2

Summary of Selected Models as Simulation Procedures to Estimate Watershed Erosion and Sediment Yield

Model	Reference	Comments
Negev	Negev (1967)	Example of a distributed erosion and sediment yield model coupled with a hydrologic model.
CSU	Simons et al. (1975); Simons and Li (1976); Li (1979)	Erosion and sediment yield in overland flow and open channel flow. Kinematic cascade model. Has been applied under a variety of conditions. Basin scale model for individual events.
ANSWERS	Beasley (1977)	Incorporates some USLE parameters and is based on a grid network to distribute parameters. Designed as a basin scale model for agricultural areas.
CREAMS	Knisel (1980a)	Erosion and sediment yield model for simple watersheds (field scale). Estimates are for an entire storm event with continuous hydrologic simulation between events. Uses some USLE parameters.

remote sensing, and map specified parameters, etc.) and the weaknesses (parameter estimates often a function of grid size, grid intersections overlap topographic features, etc.) of grid-based procedures. The CREAMS model simulates erosion and sediment yield for individual storms but uses runoff volume and peak discharge. Thus, it does not account for dynamic variations within the runoff hydrograph, except in an approximate sense. It does, however, treat spatially varied flow in the channel routing routines. The CREAMS model uses some USLE parameters and was designed to be used with a minimum amount of calibration. The CREAMS model (like the USLE and CSU models) has received wide use and will probably receive extensive use in the future.

Finally, a very useful inventory of currently available hydrologic models is given by Renard, Rawls, and Fogel (1982). They provide references, abstracts, and information on processes simulated, geographic area, and land use of 75 hydrologic models. Of these 75 models, 17 include erosion and sediment yield components. Renard, Rawls, and Fogel (1982, p. 510, Table 2) list 10 references which also summarize and catalog hydrologic models.

EXAMPLE PROBLEMS AND MORE COMPLEX MODELS

In this section, the emphasis is on problem classification and how this classification is related to model selection. This can be stated another way. If we analyze and classify a particular problem, will this information be of use in selecting the appropriate models to apply in reaching a solution?

Upland Erosion

Given the conditions of a uniform hillslope, which models might be appropriate to answer the following questions?

1. Is soil loss, on the average, likely to be limited by detachment processes or transport processes?

2. What is a reasonable range (in percent by weight) in expected sediment concentration during a "typical" runoff event?

3. What is the particle-size distribution one might expect for eroded sediment in runoff?

4. What would be the influence on sediment yield if the slope were concave or convex?

5. To meet prespecified design criteria, how would one estimate the volume of runoff and total sediment yield for a 25-year storm?

These questions, and the suggested models, are summarized in Table 3.

TABLE 3

Example Problems and Suggested Models for Each Problem Related to Erosion on a Hillslope

Question	Suggested models	Comments
1. Detachment or transport limiting	1. Kinematic wave, erosion model	Equations 21 through 31 and relation of KI to B/K used to estimate limiting factors. Choose a representative storm or storms.
2. Range in expected concentration	1. CREAMS 2. MUSLE	Can be used to compute runoff and sediment yield, and thus concentration.
3. Particle size distribution	1. CREAMS 2. CSU 3. MUSLE (SWRRB)	Calculations made by particle size classes and default values available.
4. Slope shape	1. CREAMS	Designed for this type of analysis.
5. Yields for 25-yr storm	1. CREAMS 2. MUSLE and runoff model 3. SWRRB	CREAMS designed to compute runoff and sediment yield. MUSLE needs runoff estimates. SWRRB estimates runoff and sediment yield.

Other models could be equally applicable, but of those discussed, the ones listed in Table 3 are thought to be most appropriate. For example, question 4, influences of slope shape, is particularly suited to the CREAMS model, because it was intentionally designed to address this problem. The MUSLE model may be particularly appropriate for question 5, dealing with sediment yield for a 25-year storm, because it can use runoff peak rate and volume estimates from any source, including measured values or estimates from an independent flood frequency analysis (Williams et al., 1985). If these runoff estimates are available, MUSLE can be applied directly and simply.

Sediment Yield from Larger Watersheds

Suppose estimates of total sediment yield are needed for a complex (on the order of 10 to 100 km^2 drainage area) watershed. If average annual estimates were of interest, then the USLE could be applied to several typical subareas to estimate a watershed-wide estimate of gross erosion, and this

estimate would be multiplied by a delivery ratio to estimate sediment yield. This would provide a first estimate of average annual sediment yield. As an alternative approach, a time series of runoff volume and peak rates (sufficiently long to estimate average annual values) could be used with the MUSLE to generate a time series of sediment yield estimates. A recently developed model, SWRRB, described by Williams et al. (1985), includes MUSLE in a continuous simulation model. Under conditions as encountered in the western United States, the PSIAC or Flaxman methods might be used to make estimates independent of the USLE structure and methodology.

If individual storm estimates were required, then MUSLE could be used with concurrent runoff estimates. The obvious alternative would be to use a complex simulation model, such as the CSU, ANSWERS, or SWRRB model. In any case, however, it may be useful to apply the USLE-delivery ratio, or MUSLE, or one of the regression or index methods to make a preliminary estimate. This preliminary estimate could be used as a reference point, or rough order of approximation, to compare with comparable estimates from the more complex simulation models. Finally, other procedures are available from the USDA Soil Conservation Service and the U. S. Army Corps of Engineers. In many cases, these procedures may be most appropriate for a large number of problems. Therefore, potential model users are urged to consult the material presented by Renard, Rawls, and Fogel (1982) to begin the model selection processes on a broader basis than outlined herein.

FUTURE DIRECTIONS IN RESEARCH AND TECHNOLOGY

Throughout the previous sections, specific comments were made as to the likelihood of continued use of a model in the future. This section expands on these comments in a brief fashion.

For our purposes here, forecast means to estimate or calculate in advance based on experience and an assessment of present conditions. In the present context, the intent is to forecast development of new models and techniques.

As suggested earlier, some class of problems will continue to be solved by application of the USLE. There is a need for simple, easy-to-use models with sufficiently simple structure and documented parameters values. Moreover, for a specific application, if the same results are obtained by several individuals, then the procedure has the advantage of repeatability.

If capable and dedicated individuals, assisted by institutions committed to support the models and the individuals, assist in prolonged model development and technology transfer, then their models are likely to become widely accepted. This was the case for the USLE, the Stanford model, the CSU model, the CREAMS model, and other procedures and models maintained by agencies such as the Corps of Engineers and the Soil Conservation Service. Therefore, it is likely that most of the models identified here (especially those shown in Tables 1 and 2) will continue to be used in the near future.

Development of New Models

No model, or group of models, will ever be appropriate for all problems. Thus, it would seem reasonable to assume the continued modification of

existing models and the development of new ones. A reasonable assumption might be the development of coupled partial differential equations for runoff and erosion (similar to Eqs. 21 through 27) to derive simple sediment yield equations similar to Eq. 27. Developments such as these, coupled with extensive field research programs, may produce somewhat more fundamentally based erosion/sediment yield equations comparable to the USLE in practical applications.

Improved models for simple watersheds may be developed based upon the CREAMS model structure (coupled hydrologic models and erosion/sediment yield models). These efforts may result in improved models which better represent the strong interactions between runoff and erosion and which more directly account for dynamic processes and feedback. For example, improved runoff models, which more accurately account for spatial variability in infiltration, may produce better estimates of spatial variability in erosion, sediment transport, and deposition. The lack of suitable methods to accurately predict infiltration, and thus runoff, constitutes a major limitation in the development of improved erosion/sediment yield models. If current efforts to improve infiltration models are successful, the improvements in representing runoff in erosion/sediment yield models will quickly follow.

A second major limitation is the lack of suitable methods of lumping topographic elements (and thus parameter estimates for the topographic elements) to represent large and complex watersheds in mathematical models. For example, how large an area can be represented as an upland area dominated by interrill and rill erosion? At what point is it necessary to include channel processes? Given that we know the answer to these questions, we then need to know how parameter values are affected as the size of the upland area increases. Another related example is in the representation of the steam channel network in the watershed model. How much of the detailed channel network in the prototype watershed (and remember, the number of channel segments is dependent upon the map scale selected to represent the prototype watershed) should be represented in the mathematical model? If the channel network is truncated in the model so that some of the smaller channels are ignored, then how does this affect the model performance and parameter estimates? At each stage, in representing watershed topography or geometry, there are various degrees of smoothing detail and spatial lumping. At present, there are no suitable methods of accomplishing this lumping or predicting its influence on parameter distortions or model performance. If progress is made in this general area of lumping-parameter distortion-model performance, then improvements in watershed runoff, erosion, and sediment yield models will directly follow. Additional details on necessary research, to advance our ability to understand and model many of these processes, are given in a recent state-of-the-art report (ASCE, 1982).

Applications of Expert Systems

In this section, the concept of an expert system is introduced, and the concept of embedding a mathematical model within an expert system is proposed as a method synthesizing the power of expert systems with computer simulation models.

Definition and Significance of Expert Systems

An expert system is a realization of a method to combine the experience and judgment of scientists, engineers, or other specialists with the storage ability and computational efficiency of a digital computer to obtain a solution, partial solution, or method of obtaining a solution to a particular problem.

Expert systems are described in the first chapter of a recent book (Bramer, 1982, p. 3) as follows:

> An important development, arising largely from Artificial Intelligence research which has crystallized in the past few years, is the idea of an expert system. An expert system has been defined as a computing system which embodies organized knowledge concerning some specific area of human expertise sufficient to perform as a skillful and cost-effective consultant.

The significance of expert systems is that, if successful, they provide a means of obtaining expert opinion based on education, experience, and ability, without the necessity of obtaining the experts. Of course, the systems will not approach perfection in the foreseeable future (that means they will not be as good as the actual experts) because the human brain will remain superior to any program. Perhaps, a better summary of the significance of expert systems is given in the preface of the previously cited book (Michie, 1982, p. xii) as follows:

> I do not believe that there is a more important theme for computer-based industry today than the new craft of knowledge engineering, nor one whose ramifications reach further into all corners of intellectual, social, and economic life. If one sees, as I do, the computer-based expert system as a common model for knowledge-driven transactions of all kinds, from advising a commercial client to planning the economy, from training a student to instructing an industrial robot, then it should be plain to all that whichever community can first master the new technology can expect to obtain a decisive advantage.

Examples of Expert Systems

Three existing expert systems can serve as useful examples in describing such systems in preparation for consideration of systems development for computing erosion and sediment yield. Bramer (1982, Table 1, pp. 8-11) lists 35 expert systems and classifies them according to area of application, while providing references and brief descriptions of each system. Three of these systems are briefly described in Table 4.

The PROSPECTOR expert system was developed to aid in evaluating a site or region for mineral deposits. Output from the program includes probability statements as to the occurrence of a mineral deposit at the site. This system is also interactive and can trace or explain how a particular probability (a decision, in this case) was reached. The PROSPECTOR system would appear to have significant potential for applications in mineral exploration. It also may continue to serve as a prototype system in the future.

Expert Systems for Runoff, Erosion, and Sediment Yield

From the examples shown in Table 4 and the previous discussions as to the need for experience and judgment (i.e., experts) in applying and interpreting models for runoff, erosion, and sediment yield, it appears that there

TABLE 4

Selected Examples of Expert Systems*

System	References	Comments
DENDRAL (chemistry)	Feigenbaum et al. (1971)	An early system developed at Stanford to identify organic compounds using data from mass spectrograms.
MYCIN (medicine)	Shortliffe (1976)	Developed to diagnose and recommend appropriate drug treatment for infectious diseases (blood diseases and meningitis). Designed for interactive use. Includes procedures to "explain" how a recommendation was reached.
PROSPECTOR (geology)	Duda et al. (1979)	Developed at SRI International to aid in evaluating a site or region for mineral deposits. Designed for interactive use. Also includes explanation features.

*As summarized by Bramer (1982) in a Review of Expert Systems Research.

y be potential for expert systems applications in these areas. For exam-, even a model as simple as the USLE requires the application of judg-nt in selecting appropriate C factors.

A USLE-based expert system, much like those shown in Table 4, would ɔear to be possible and should be of benefit for a wide class of users. Such ɔystem could conduct an interactive dialogue with the user to first ascer-ɪn if the USLE is appropriate for the problem. Once this was established, ɜen information could be obtained to evaluate the factors, including applica-ions of expert knowledge in estimation of the C factor. Next, the USLE soil ɪss estimates could be subject to expert interpretation with respect to the broader aspects of the user's problem (e.g., ranking conservation measures, selecting support practices to meet specified soil loss tolerances, etc.). This proposed application provides a hint of the new application or modification of expert systems proposed herein.

The major difference between traditional expert systems, such as those summarized in Table 4, and the expert systems proposed here, is that, rather than only building in a fixed number of rules or conditions, a simulation model (such as CREAMS) could be embedded within the expert system. The fixed conditions or rules would be used to provide input data and parameter values for the model, and then to interpret the simulation results or model output. With this type of system, the number of conditions or rules remains fixed at a relatively small number, but there are an infinite number of possible simulations. The addition of simulation capability (including sensitivity analysis and predictive capability) to an expert system would enhance the system's ability to examine a problem using a "What if?" approach.

SUMMARY

Many contaminants, such as actinides, in the environment are strongly associated with the soils compartment. Processes which affect soil can thus

affect soil-associated contaminants. Physical transport processes (e.g., erosion and sediment transportation and deposition) result in redistribution of sediment-associated contaminants and usually involve fine particle and contaminant concentration enrichment.

Recent advances have improved our understanding of these physical transport, particle sorting, and enrichment processes. Recently developed erosion and sediment yield models directly incorporate physical mechanisms controlling enrichment and thus have improved our understanding of physical mechanisms important in contaminant transport.

Watershed processes controlling erosion and sediment yield are described in detail, as are two upland erosion models (USLE and the kinematic model). Better understanding of these processes and their models is required to address some of the more subtle and fundamental problems in sediment-associated contaminant transport and redistribution.

Models for application on more complex watersheds are described, and example problems are presented which suggest how they might be applied on watersheds. The state-of-the-art in development of such models is described and discussed. Sufficient information is presented to allow a potential model user to decide which erosion-sediment yield models might be most appropriate to predict sediment-associated contaminant transport and redistribution.

Expert systems are described and discussed relative to past applications and new applications in modeling erosion and sediment yield. The concept of an embedded simulation model within an expert system is introduced. Such a system as described might, in turn, be embedded within a contaminant inventory-transport-redistribution model.

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